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THE NATURE OF THE FAINT *CHANDRA* X-RAY SOURCES IN THE GALACTIC CENTRE

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ABSTRACT

Recent *Chandra* observations have revealed a large population of faint X-ray point sources in the Galactic Centre. The observed population consists of $\gtrsim$ 2000 faint sources in the luminosity range $\sim 10^{31}$-10^{33} erg s^{-1}. The majority of these sources (70%) are described by hard spectra, while the rest are rather soft. The nature of these sources still remains unknown. Belczynski & Taam (2004) demonstrated that X-ray binaries with neutron star or black hole accretors may account for most of the soft sources, but are not numerous enough to account for the observed number and X-ray properties of the faint hard sources. A population synthesis calculation of the Galactic Centre region has been carried out. Our results indicate that the numbers and X-ray luminosities of intermediate polars are consistent with the observed faint hard Galactic Centre population.

Subject headings: Galaxy: center — X-rays: binaries — stars: white dwarfs

1. INTRODUCTION

A *Chandra* X-ray survey of the Galactic Centre (GC, Wang, Gotthelf & Lang 2002) first revealed the presence of $\sim$ 1000 spectrally hard X-ray sources (2-10 keV) with luminosities $L_{\rm x} \lesssim 10^{35}$ erg s^{-1}. Pfahl et al. (2002) have claimed that wind-fed neutron stars (NS) with intermediate- and high-mass companions are responsible for a significant fraction of the hard sources in the Wang et al. (2002) survey. A deeper *Chandra* survey of the nuclear bulge region (Muno et al. 2003; hereafter MM03) revealed over 2000 X-ray point sources with X-ray luminosities $\sim 10^{31}$ -10^{33} erg s^{-1}. The majority of these sources (1427) are described by hard spectra (with a photon index of an absorbed power law $\Gamma < 1$), while the rest (652) are characterized by softer spectra ($\Gamma > 1$).[1] Belczynski & Taam (2004; hereafter BT04) have studied the entire population of X-ray binaries with NS and black hole (BH) accretors in the context of the MM03 survey. It was demonstrated that neither wind-fed (low-, intermediate-, high-mass) systems nor Roche Lobe Overflow (RLOF) binaries can explain the entire faint population. However, the quiescent transients may be responsible for most of the faint soft GC sources. Muno et al. (2004) suggested that the observed faint hard sources are most likely intermediate polars (IPs); a subclass of magnetic cataclysmic variables (CVs).

Among magnetic CVs, IPs are asynchronous rotators, with the white dwarf (WD) spin period being shorter than the orbital period. Currently there are $\sim$ 31 IPs known (Gansicke et al. 2005). They consist of a magnetized WD and a low-mass companion. The companion transfers mass via RLOF to the WD, with typical mass transfer (MT) rates of $\sim 10^{-11}$ M$_\odot$/yr. Matter spirals in toward the WD forming an accretion disc, which is truncated by the WD magnetosphere. Matter is then channeled into accretion columns over both magnetic poles of the WD (e.g., Belle et al. 2005). Typical IP magnetic fields are ≤ 10 MG (de Martino et al. 2004). It is from below the accretion shock, above the WD surface, where the hard X-rays originate (see Warner 1995; Patterson 1994 for review). IPs are known to exhibit both soft and hard X-ray emission and are thought to be the most luminous subclass of CVs in X-rays, owing to their typically higher MT rates.

We address the issue of the nature of the faint hard source population observed in the deep GC exposure of MM03, and test the validity of the Muno et al. (2004) hypothesis that these sources are IPs. We construct a simple phenomenological model of an IP and use population synthesis (§ 2) to calculate the number of IPs and their X-ray luminosities in the GC (§ 3). In § 4 we comment on other population synthesis studies and discuss our results in context of available observations.

2. MODEL DESCRIPTION

We use the updated population synthesis code `StarTrack` (Belczynski, Kalogera & Bulik 2002; Belczynski et al. 2005a). All stars are evolved with solar metallicity (Z=0.02) and with standard wind mass loss rates. We assume a continuous star formation rate in the GC over the last 10 Gyrs, and a binary fraction of 50%. Several physical processes important for binary evolution are accounted for: tidal interactions, detailed MT calculations, common envelope (CE) events, supernovae explosions, and various mechanisms for angular momentum losses such as magnetic braking (MB) and gravitational radiation (GR), among others.

The goal of this study is to test the hypothesis that IPs can account for the observed population of the faint hard X-ray point sources in the GC. We use our standard model (Belczynski et al. 2005a) to check whether within the general framework of binary evolution, the number of predicted IPs coincides with that of the GC faint hard sources. It has been realized that CVs are the likely outcome of the CE phase (Paczynski, 1976). Despite years of investigation, no consistent physical model for this phase

[1]Foreground sources excluded; M.Muno, private communication.

of binary evolution exists. Therefore, we use two current alternative pictures of CE evolution to provide an estimate of associated model uncertainties. Our standard CE model calculations assume energy balance (Webbink 1984); the donor envelope is ejected from the system at the expense of the binary orbital energy. The binary separation following the CE phase depends on parameters $\alpha_{\rm ce}$ and λ, relating to the efficiency with which the orbital energy is used to expel the CE from the system, and donor internal structure, respectively. We adopt $\alpha_{\rm ce} \times \lambda = 1.0$. In our alternative CE model, we have adopted the prescription of Nelemans & Tout (2005) which employs angular momentum balance, and assumes that the angular momentum is lost from the binary in a linear fashion as a function of mass loss. Following Nelemans & Tout (2005), we adopt a scaling factor $\gamma = 1.5$ for this model. See Belczynski, Bulik & Ruiter (2005b) for the CE equations.

X-ray Luminosity Calculation. We assume that the IP X-ray luminosity is a function of the accretion rate, accretor physical properties, and the efficiency with which the accretion luminosity is converted to hard X-ray luminosity in the *Chandra* band.

For degenerate donors ($M_{\rm don}$), we assume that MT is GR-driven and calculate it via

$$\dot{M}_{\rm don} = M_{\rm don} D^{-1} \frac{dJ_{\rm gr}/\,dt}{J_{\rm orb}} \quad (1)$$

$$D = \frac{5}{6} + \frac{1}{2}\zeta_{\rm don} - \frac{1-f_{\rm a}}{3(1+q)} - \frac{(1-f_{\rm a})(1+q)\beta_{\rm mt} + f_{\rm a}}{q} \quad (2)$$

where $J_{\rm orb}$ is the orbital angular momentum, $dJ_{\rm gr}/dt$ is the angular momentum loss due to GR, $f_{\rm a}$ is the fraction of transferred mass accreted by the WD of mass $M_{\rm acc}$ (we assume Eddington limited accretion; see below), $q \equiv (M_{\rm acc}/M_{\rm don})$, and $\beta_{\rm mt} = M_{\rm acc} M_{\rm don}^2/(M_{\rm don} + M_{\rm acc})^2$. The radius mass exponent for the donor $\zeta_{\rm don}$ is obtained from stellar models (see Belczynski et al. 2005a).

For non-degenerate donors we estimate the MT rate as follows:

$$\dot{M}_{\rm don} = -\frac{\zeta_{\rm evl} + \frac{2}{\tau_{\rm mb}} + \frac{2}{\tau_{\rm tid}} + \frac{2}{\tau_{\rm gr}}}{\zeta_{\rm don} - \zeta_{\rm lob}} M_{\rm don} \quad (3)$$

where $\zeta_{\rm evl}$ is the change of the donor radius due to its nuclear evolution, $\zeta_{\rm lob}$ is the radius mass exponent for the donor Roche lobe, and $\tau_{\rm mb}$, $\tau_{\rm tid}$ and $\tau_{\rm gr}$ are the timescales associated with MB, tidal interactions and GR, respectively. In some cases MT proceeds on a thermal timescale, and thus we use $\dot{M}_{\rm th} = -M_{\rm don}\tau_{\rm th}$ where the thermal timescale may be obtained from $\tau_{\rm th} = (30 \times M_{\rm don}^2)/(R_{\rm don} L_{\rm don})$ (e.g., Kalogera & Webbink 1996). Then, we can calculate mass accretion rate as $\dot{M}_{\rm acc} = \min(0.95 \times \dot{M}_{\rm don}, \dot{M}_{\rm edd})$. We limit the accretion rate to the critical Eddington rate ($\dot{M}_{\rm edd}$), such that if MT is super-Eddington, the excess material leaves the binary with the specific angular momentum of the accretor. We impose a mass-loss rate of 5% in the sub-Eddington regime since some IPs are observed to experience a mass loss rate of few percent ($\sim$ 10% in the extreme case of AE Aqr; Wynn, King & Horne 1997).

The hard *Chandra* band X-ray luminosity of an IP system is calculated from

$$L_{\rm x} = \eta_{\rm bol}\,\eta_{\rm geo}\,L_{\rm bol} = \eta_{\rm bol}\,\eta_{\rm geo}\,\epsilon\,\frac{GM_{\rm acc}\dot{M}_{\rm acc}}{R_{\rm acc}} \quad (4)$$

where G is the gravitational constant, ϵ is the conversion efficiency of gravitational binding energy to radiation (1 for WD surface accretion), and $M_{\rm acc}$ and $R_{\rm acc}$ are the accreting WD mass and radius, respectively. We use $\eta_{\rm bol} = 0.09$ for the bolometric correction to 2-8 keV X-ray luminosity, although it is noted that this value is quite uncertain and may span a wide range ($\sim$ 0.01-0.2; Norton & Watson 1989b). The IP X-ray emission is likely anisotropic to some extent, since the accretion proceeds through the WD magnetic poles. However, it has been demonstrated that the emission region in IPs may be quite extensive (i.e., may encompass more than a quarter of the WD surface, Norton & Watson 1989a) and thus the anisotropy is not expected to be large. Here we assume isotropic emission and so $\eta_{\rm geo} = 1$, although we note that a more sophisticated model including polar cap accretion should be invoked once more observations are available. In general $\eta_{\rm geo}$ depends on the size of the emitting regions and their relative orientation to the observer.

Initial Conditions. The initial mass of single stars and the primary (more massive) components in binaries are drawn within the range 0.8-150 $M_\odot$ from a broken three-component power law initial mass function (IMF), with a slope of -1.3/-2.2/-2.7 in mass ranges 0.08-0.5/0.5-1/1-150 $M_\odot$ (Kroupa, Tout & Gilmore 1993). The secondary mass is obtained through a flat mass ratio distribution. Initial binary orbits are specified by semi-major axis (distribution flat in the logarithm $\sim 1/a$) and eccentricity (thermal distribution $\sim 2e$).

The stellar population of the GC is evolved through 10 Gyr (age of the Galaxy) with a constant star formation rate and IP systems are extracted and luminosities compared against the MM03 survey sources. We call *any* binary system experiencing RLOF in which the accretor is a WD and the donor is any type of star a CV (i.e. including AM CVn systems, see Warner 1995). We consider various types of WDs: helium (HeWD), carbon-oxygen (COWD), oxygen-neon (ONeWD), hydrogen (HWD; formed by stripping the envelope of a low-mass main sequence (MS) star in RLOF), and hybrid (HybWD; containing a He envelope and a He-C-O mantle, formed by stripping of a low-mass He star in RLOF). We note that the evolution of IPs and CVs are identical in our model, i.e., we do not incorporate the magnetic field of the WD into the evolution. Rather, from the CV population we assign a fraction of CV systems that are IPs. In our model we adopt an IP fraction ($\rm IP_{frac}$) of 5% following MM03. We have calibrated our results to pertain to the surveyed GC region by scaling by stellar mass. Following Muno et al. (2004; see their § 3), we have assumed that the 17'×17' *Chandra* field of view of the GC corresponds to a cylinder 440 pc deep with a radius of 20 pc, encompassing 1.3×10^8 $M_\odot$ in stars[2].

3. RESULTS

[2]There may be 50% uncertainty associated with this estimate (Launhardt et al. 2002), which will propagate linearly in our results.

It is found that the synthetic GC population of IP systems span a range of X-ray luminosities $\sim 3\times10^{29}-5\times10^{33}$ erg s^{-1}. In the following we only discuss systems above the MM03 survey detection limit, i.e., with X-ray luminosities $\geq 10^{31}$ erg s^{-1} unless otherwise noted. The main results of our calculations for the standard and alternative CE prescriptions are presented in Table 1 and Figure 1.

Standard CE model. The number of IPs depends strongly on the adopted IP$_{\rm frac}$. We find $\sim$ 800-8000 IPs in the GC for IP$_{\rm frac}$ of 1-10%, respectively. To match the observed number of faint hard X-ray sources in the GC (1427) with IPs we would require an IP$_{\rm frac}$ of $\sim 2\%$. The distribution of orbital periods of our IPs peaks between $\sim$ 1.5-3.5 hr and extends toward longer periods (≥ 5 hr), which is in agreement with the observed orbital periods of magnetic CVs (see i.e., Tovmassian et al. 2004). We find that the most frequent IP type (89%) is a magnetic WD accreting from a MS star. The majority of donors (87%) are ≤ 0.7 M$_\odot$, i.e. K-M dwarfs. Accretors in the WD-MS subclass are COWDs (66%) and HeWDs (23%). The second most frequent (10.5%) type of IP is a double degenerate system (i.e., close WD-WD binary with stable RLOF). The most common configurations found within this subclass are: COWD-HeWD (6.6%), COWD-HybWD (1.7%) and COWD-HWD (1.7%). Finally, we find few (0.5%) IPs with giant-like donors. In this subclass nearly all systems consist of a low-mass ($\sim 0.3-0.4$ M$_\odot$) sub-giant or a red giant transferring mass to a COWD. The relative occurrence frequencies of different IP types reflect various evolutionary timescales for donors of varying types and masses. The WD-MS IPs are abundant since low-mass MS stars have very long evolutionary timescales ($\sim 10^{11}$-10^{12} yr) and RLOF at the IP phase is also driven on long timescales; by GR ($\tau_{\rm gr} \sim 10^{10}$ yr) with the addition of MB ($\tau_{\rm mb} \gtrsim 10^9-10^{10}$ yr) for some systems. The evolution of double degenerates is driven by GR on shorter timescales on the order $\tau_{\rm gr} \sim 10^9$ yr (since these binaries are tighter); moreover it is difficult to form these systems (survival of two CE phases rather than one). For WD-giant donor systems, the evolutionary and MB timescales are shorter than in the above cases, making them the least represented subclass of IPs.

In Figure 1 we show the overall luminosity distribution and the corresponding X-ray luminosity function (XLF) for the model IPs. The IPs above the MM03 detection limit are marked for easy comparison. It is noted that only $\sim 55\%$ of IPs are bright enough to make the X-ray luminosity threshold of the survey. The brightest IPs in our simulations are those with giant donors, with average X-ray luminosities $L_{\rm x} \sim 5\times10^{32}$ erg s^{-1}. The power-law slope of the cumulative distribution ($N(>L_{\rm x}) \sim L_{\rm x}^{-\beta}$) of the XLF for the synthetic IPs (above the survey detection limit) is $\beta \sim 0.8$. This value is shallower than the one derived by MM03[3] (1.34 for $L_{\rm x} > 4\times10^{31}$ erg s^{-1}) and Muno et al. (2006). It is noted that the full XLF slope modeling for IPs would require *i*) taking into account absorption toward the GC sources (as well as circumbinary absorption), and *ii*) a detailed model of anisotropic X-ray emission from a magnetized WD.

Alternative CE model. It is found that $\sim$ 170-1700 IPs may be present in the GC for IP$_{\rm frac}$ of 1-10%, and one would require an IP$_{\rm frac}$ of $\sim 8\%$ to match the number of GC faint hard sources. Orbital periods are found in the same range as for the standard CE model. Once again, the most frequent IP type is a magnetic WD accreting from a low-mass MS star (90.8%) with the majority of them being COWD-MS star binaries (75%). Double degenerates are the second most populated subclass (8.6%), first with COWD-HWD (4%), followed by COWD-HeWD and then COWD-HybWD (2.1% and 1.9%, respectively) with other types constituting the rest. Again only a small fraction (0.6%) of the IPs involve a WD-giant star binary. The slope of the XLF for IPs above the survey detection limit is found again to be $\beta \sim 0.8$ (see Fig 1).

Additionally, we have calculated a model with decreased CE efficiency ($\alpha_{\rm ce}\times\lambda = 0.1$). The number of IPs decreases by $\sim 50\%$, due to the more frequent binary mergers during CE phases. Also, we have tested the assumption on the initial mass ratio of binary components with a model in which both binary component masses are chosen independently from the IMF. The overall binary evolution is quite different, since on average q is much smaller (~ 0.1, as opposed to the flat q-distribution in other models). There is an overall increase ($\sim 20\%$) in the number of IPs, though the population content is very similar with 89% of IPs with $> L_{\rm x}10^{31}$ erg s^{-1} being MS-WD binaries.

Typical evolution. Two MS stars (2 and 0.6 M$_\odot$) start out on a highly eccentric orbit (e=0.9) with an orbital period of 1460 days when the Galaxy is 2.1 Gyr old. At 3.6 Gyr the system has circularized (period of 109 days), a CE phase is initiated by the primary (now an asymptotic giant), and upon ejection of the envelope the orbital period shrinks by $\sim$ two orders of magnitude (now 16 hours). The primary shortly thereafter becomes a COWD. At 8.4 Gyr the MS secondary initiates RLOF and the system becomes an IP. At 10 Gyr we find an IP system with a period of 2.9 hours. We note that for this same system, if the alternative CE prescription model is used an IP is never formed. The reason for this is that upon ejection of the CE, the binary does not lose enough orbital angular momentum in order to end up in a tight enough orbit such that RLOF, and an IP phase, can ensue. Hence a smaller number of IPs are found in our alternative CE model.

4. DISCUSSION

We have explored the possibility that the faint hard sources in the GC are IPs. It is found that for both current CE models, the IP population is ample enough to explain the GC faint hard sources. The required IP fractions are then $\sim 2\%$ and $\sim 8\%$ for the standard and alternative CE models, respectively. The actual fraction is uncertain and currently estimated to be $\sim 5\%$ by MM03 based on the Kube et al. (2003) catalog of CVs. Once more stringent observational constraints on the IP fraction are obtained, we will be able to test the validity of different CE models.

At this point a full picture of the GC X-ray point sources begins to emerge. Most of these sources are faint and are spectrally hard (1427) and can be explained by a population of IPs as suggested by Muno et al.(2004) and confirmed in this study. Additionally, there may be a small

[3] Although formula (5) in MM03 does not represent a cumulative distribution, the listed value of the slope is cumulative; M.Muno private communication.

contribution ($\sim$ few percent) of wind-fed sources with NS and BH accretors to the faint hard population, as proposed by Pfahl et al. (2002) and later revised by BT04 and Liu & Li (2005). The faint soft sources (652) are likely RLOF transients with NS and BH accretors in quiescence as proposed by BT04. The bright GC sources ($\lesssim$ 20; Wang et al. 2002 and MM03) can be explained by a population of NS/BH persistent sources and transients in outburst (e.g., BT04). The stellar density of the GC region is higher than that of the solar neighbourhood, so it's possible that dynamical interactions may alter the number of CVs in the GC. Tidal captures or exchange interactions may increase the numbers, but also, the primordial CV population may be depleted by tidal disruptions in dense environments (i.e., see Heinke et al. 2003). A full evolutionary model of the GC incorporating binary stellar evolution and dynamical interactions should be invoked to gauge these processes. Here, we have just demonstrated that field-like (no stellar interactions) evolution provides enough IPs to explain the GC faint hard X-ray population.

Liu & Li (2005) conducted a different population synthesis study of the GC sources, and it was found that most of the *Chandra* sources are NS Low Mass X-ray Binary transients, with IPs playing a minor role in the Wang et al. and the MM03 surveys. The IP MT rates obtained by Liu & Li are much lower ($\sim$ 2 orders of magnitude) than our predictions and those of observational estimates. This leads to an underestimate of IP X-ray luminosity in the Liu & Li (2005) simulations, and hence a severe underestimate of IP numbers in the GC. The Liu & Li (2005) model is based on the population synthesis code by Hurley, Tout & Pols (2002). MT is calculated from a formula that does not directly incorporate the star's response to mass loss, nor the various mechanisms for angular momentum loss. It was originally obtained and calibrated for binary systems with evolved donors (Algols; Tout & Eggleton 1988) and does not appear to work for low mass IP donors.

We have found that most of the Galactic Centre IPs are either magnetic WDs feeding from low-mass MS late-type companions, or double degenerate systems (e.g., AM CVn). These systems are very unlikely to be detected at wavelengths other than X-rays due to the high extinction toward the GC, and the low luminosity of the IP systems (K-M dwarfs). Recently, Laycock et al. (2005) carried out a search for infrared counterparts of the GC X-ray sources. It was found that high mass X-ray binaries (with donors brighter than B2V) are unlikely candidates for the majority of the GC faint sources, in agreement with our findings and those of BT04. Bandyopadhyay et al. (2005) are conducting a deeper near-infrared survey which will detect all giant type donors and MS donors with spectral types earlier than G. However, if the typical donors in IPs are indeed K-M MS stars, as found in our study, and also observed for most Galactic IPs (e.g., M3 V for EX Hya, Dhillon et al. 1997; K5 V for AE Aqr, Tanzi et al. 1981), these systems will go undetected in this survey.

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Table 1
Galactic Centre Population of IPs

Model	WD-MS	WD-giant	WD-WD	Total
Standard CE				
IP_{frac} 1%	694	5	82	781
IP_{frac} 5%	3474	25	410	3909
IP_{frac} 10%	6948	50	820	7818
Alternative CE				
IP_{frac} 1%	157	1	14	172
IP_{frac} 5%	784	5	74	863
IP_{frac} 10%	1568	9	149	1726

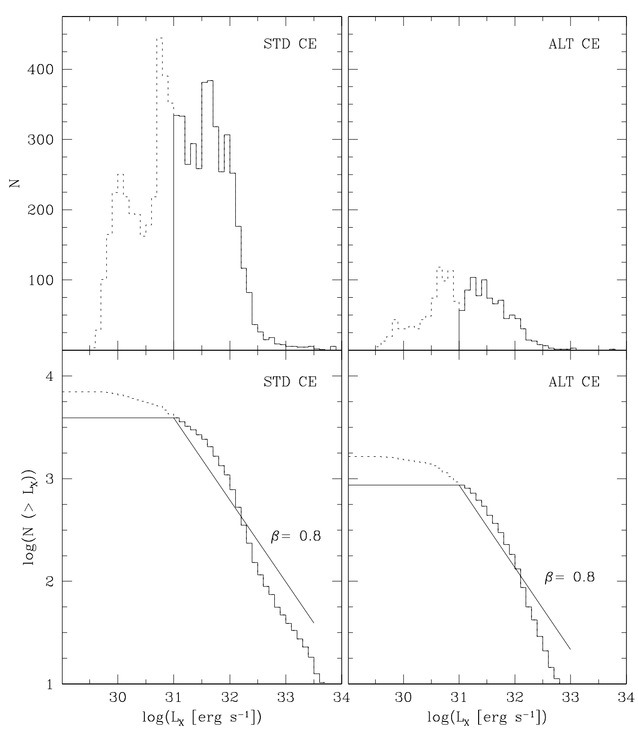

Fig. 1.— Left: X-ray luminosity distribution and corresponding XLF for GC IPs for the standard CE model and an IP fraction of 5%. The entire population is shown with a dotted line while IPs brighter than the MM03 X-ray luminosity threshold are shown with a solid line. The XLF slope of the cumulative distribution ($N(> L_{\rm x}) \sim L_{\rm x}^{-\beta}$) is marked. Right: same as the left panels but for the alternative CE model.